Extreme Stars

At the Edge of Creation

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Chapter 1

Sun and stars

Our ordinary Sun provides a baseline, a standard against which we compare other stars, against which stellar limits can be tested. Though it does not begin to approach the limits of stellar properties it is still a wonder. Even at a distance of 150 million kilometers (93 million miles) it provides sufficient light and heat for us to thrive. The Sun's properties amaze. One-and-a-half million kilometers (860,000 miles, 109 Earth diameters) across, it could hold a million planets like ours. At its gaseous "surface," its opaque "photosphere" from which sunlight streams to space, the temperature is nearly 6000 degrees kelvin. (Kelvin degrees, K, are Celsius degrees above absolute zero, $-273\,°$C. Throughout the text, "degrees" is commonly dropped and the temperatures expressed simply as "kelvin;" the Sun's temperature is therefore given as 6000 kelvin or 6000 K.) The fiery gaseous center reaches an awesome 15 million K at a density 14 times that of lead. The Earth's mass, measured from the strength of its surface gravity and radius, is 6×10^{27} grams, 6000 million million million metric tons. The Sun, of which the Earth is a minor satellite, weighs in 333,000 times more, at 2×10^{33} grams (the number derived from the Earth's orbital characteristics). The solar luminosity (the amount of energy our star produces as a result of compression through gravity and thermonuclear reactions in the heat of its core) is far beyond anything that humanity will ever produce. Shining with 4×10^{26} watts, the equivalent of 4 million million million million hundred-watt light bulbs, it releases the world's annual energy production in one ten-millionth of a second. And it has been doing so for 4.6 billion (4600 million) years.

Solar surface, solar light

Though unassuming when compared with other stars, the Sun has an outstanding characteristic that allows us think of it as extreme, as one at the edge: it is close to us, and we know far more about it than we do any other star, so much that theories cannot keep up with observational knowledge. To the eye alone, this magnificent

Figure 1.1. Stars seemingly pile upon stars in this photograph of the Milky Way in Cygnus. Seen from a great distance, our Sun would be just one of them, an ordinary star in the middle of an immense range of stellar properties. [From the *Atlas of the Milky Way*, F. E. Ross and M. R. Calvert, University of Chicago Press, 1934. Copyright Part 1 1934 by the University of Chicago. All rights reserved. Published June 1934.]

body appears as a perfect, featureless, yellow-white circle against the blue sky. (Do not, of course, try to look at the Sun or any solar feature without a professionally-made filter and a good knowledge of how to use it; exposure to full sunlight for even a fraction of a second can permanently damage the eye.) Use a telescope, however, and – as first discovered by Galileo in 1609 – a variety of features pop out. Toward the edge of the solar circle, the solar "limb," the Sun darkens noticeably. A closer look reveals the apparently smooth solar surface to be broken into thousands of tiny bright granules at the limit of vision. Make a movie and speed up the action, and the surface seethes with energy, the granules bubbling and boiling like a pot of oatmeal,

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each tiny fleck lasting only a few minutes. The gases of the photosphere (and those far below) are in a state of convection, hot gases rising and losing their heat by radiation, cool gases falling.

The most obvious features are dark, seemingly black, spots set against the brilliant solar light. A few appear singly, but most of them are social, clumping into groups. Surrounding the spots are subtle white patches. The spots near the solar center are round, while those near the limb are distinctly elliptical. What appears as a disk is really a sphere, the spots near the edge appearing foreshortened. If you observe the Sun day after day, you find that the spots are not permanent features but come and go, new ones replacing old ones, some groups of them lasting a month, other simple spots a mere day. All, however, march steadily across the solar surface. This great body is rotating, taking 25 days at the equator for a full turn, but closer to 30 days near the poles, testimony to the Sun's gaseous nature, as a solid cannot behave this way. The Sun's average density (found from its mass and volume) is near that of water (one gram per cubic centimeter, 1 g/cm^3). A solid or liquid this massive would be much denser. The Sun must therefore be gaseous, not just at the surface, but throughout, even at its ultradense center.

The key to understanding the solar nature can be found on a summer afternoon. A thunderstorm flees to the east. Sunlight peeks from under the departing clouds and shines upon still-falling drops of rain, and a rainbow frames the sky, a circle of colors – red, orange, yellow, green, blue, violet – centered upon the point directly opposite the Sun. Yellowish sunlight actually consists of an array, a spectrum, of different colors that have been spread out by the light's passage through the raindrops. Isaac Newton created the same effect when he passed sunlight through a prism.

The explanation of the rainbow lies in the nature of light. Light behaves as a travelling electromagnetic wave with alternating electric and magnetic fields speeding along at 300,000 kilometers (186,300 miles) per second. It can also be thought of as a collection of particles – photons – that in a crude sense carry a chunk of wave along with them. Either way, light carries energy, and is the chief way energy is transported in

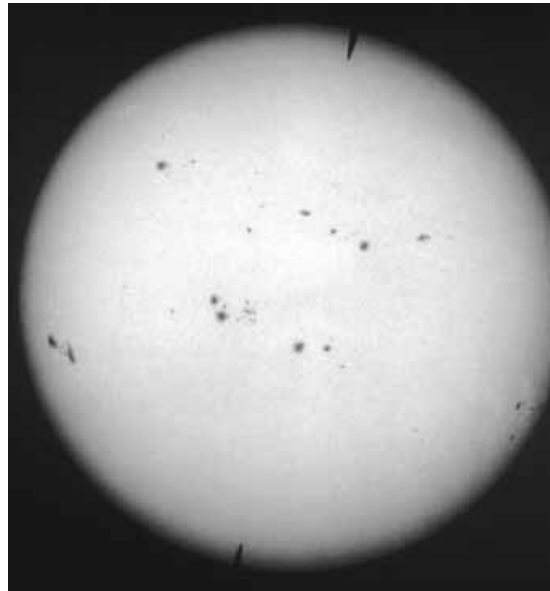Figure 1.2. The Sun, 1.5 million km and 109 Earths across, contains 333,000 times the mass of Earth and 1000 times the mass of Jupiter. The spots, areas cooled by strong magnetic fields, are foreshortened near the solar limb, showing the Sun to be spherical. The darkening at the limb shows the solar gases to be slightly transparent and the solar temperature to climb inward. [Mt Wilson and Las Campanas Observatories.]
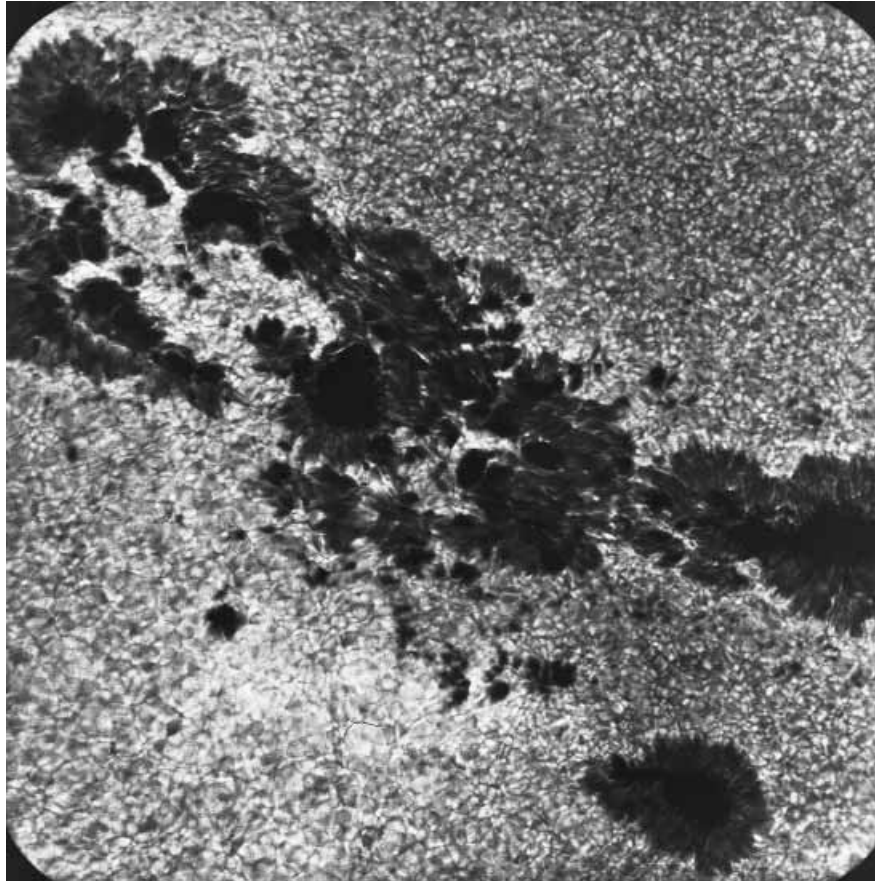
Figure 1.3. Sunspots have dark inner zones surrounded by lighter rings that are striated toward the surrounding photosphere, which is heavily granulated by convection. Convection is reduced in the spot by intense magnetism, cooling the gas and dampening the flow of radiation. [AURA/NOAO/NSF.]

the Universe. The color we associate with the light depends on the wavelength, the distance between successive wave crests. Red light, at one edge of the rainbow, has a wavelength of about 7×10^{-5} cm (0.00007 cm), violet, at the other, a wavelength of 4×10^{-5} cm. To rid ourselves of exponents, we use a more appropriate unit, the ångstrom (Å), 10^{-8} cm long. Red light therefore has a wavelength of 7000 Å, violet 4000 Å, the other colors falling in between.

There is no reason that Nature should stop radiating at these wavelengths; this range is just all we can see with the eye. Beyond red, infrared radiation is felt as heat; beyond even that, as wavelengths approach a millimeter, we call them radio waves and use them to broadcast information. Shorter than violet lies the ultraviolet, in the 100 ångstrom realm, X-rays, closer to 1 Å, the "gamma rays." The amount of energy carried by a photon depends on its wavelength, shorter-wave photons carrying more

energy than longer-wave photons. Ultraviolet waves that get through the Earth's atmosphere produce burns and protective tanning; at shorter wavelengths radiation can kill; gamma rays, for example, are produced in atomic bomb explosions. Longer waves, however, are relatively benign: you can stand all day under a high-powered radio transmitter with perfect safety.

Any body with a temperature above absolute zero will attempt to radiate its energy away. Since temperature is a measure of the energy inherent in a body, the hotter the body, the greater its ability to radiate at more energetic wavelengths. At 3 K, all that is produced is radio waves; at 300 K, infrared (in addition to radio) is radiated, but there is insufficient energy to produce X-rays, which take closer to 300,000 K. Moreover, the greater the temperature, the greater the total amount of energy radiated. Around the turn of the twentieth century, this concept was quantitatively codified into a variety of radiation laws. A solid or pressurized gas (like that in the Sun) radiates a "continuous spectrum" that depends on its temperature. From a heated body all wavelengths down to a critical limit are present; a graphical representation shows no gaps, breaks, or jumps; as we ascend from longer to shorter wavelengths, the intensity (amount) of radiation first slowly increases to a peak at a characteristic wavelength then suddenly drops.

As temperature increases, two things happen. First, more radiation pours out at every wavelength, the amount being proportional to the fourth power of the temperature (double T and the intensity of the radiation per unit area climbs by a factor of $2 \times 2 \times 2 \times 2 = 16$), a rule called the "Stefan–Boltzmann law." Second, and intimately related, the wavelength of maximum radiation shifts shortward in inverse proportion to temperature, the "Wien law." From either rule we can find T from the spectrum, either by determining the total amount of energy radiated per unit area or by finding the position of the peak, the wavelength at which the object is brightest. We cannot of course make such a measure by just looking at the spectrum, but must use a device that can sense the actual amount radiated at each point, a "spectrograph."

These principles explain the colors of the stars in the nighttime sky, reddish stars cooler than white ones (which have their radiation peaking in the middle of the visual spectrum) and white ones cooler than bluish ones. They also explain the darkening at the solar limb. For the limb to be darkened, the gas of the photosphere must be somewhat transparent so that we look a short distance into it. Since the Sun is spherical, we do not see as deeply when we look away from the center as we do at the center itself, as our line of sight enters at an angle. Because the limb is darker (and redder as well), the higher-level gases must be cooler to radiate less energy. Limb darkening not only supports the concept that the Sun is gaseous, but also shows that temperature increases inward.

This temperature increase has a profound effect on the solar spectrum. When we look at the solar spectrum in sufficient detail, we find that it is *not* continuous. Crossing it are vast numbers of dark gaps that cut out extremely narrow bands, or "lines," of color. Over the past century, each of these lines has been identified with a specific chemical element or compound. In the simplest sense, any given chemical
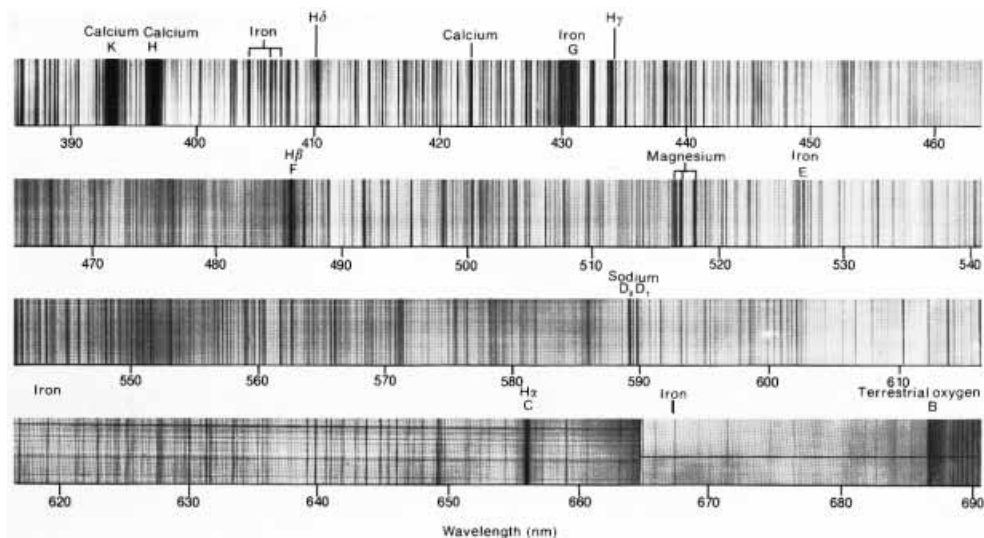
Figure 1.4. The solar spectrum, from the violet at upper left into the red at lower right, contains thousands of absorption lines of common metals. The scale is nanometers (1 nanometer = 10 ångstroms). The strongest lines are those of ionized calcium, followed here by hydrogen (H) and neutral magnesium and neutral sodium. The Roman letters B, C, F, H, K, L,etc. are from an older designation system. Three-quarters of the natural elements have been identified in the solar spectrum, and the others are surely there. [AURA/NOAO/NSF.]

element is made of an atom that has a central nucleus composed of protons, which carry positive electric charges, and neutral neutrons (particles with no electric charge, hence the name). Hydrogen, for example, always has a single proton, whereas helium has two, carbon six, iron 26, uranium 92. The nucleus is normally surrounded (loosely, orbited) by a number of negatively-charged electrons equal to the number of protons, rendering the atom electrically neutral. Since positive and negative charges attract each other, the electrons and protons are bound together. If any electrons are missing – a result of collisions between atoms – the atoms become positively charged "ions" that have absorptions completely different from those of their parent atoms and can therefore be uniquely identified.

The electrons of the atom or ion are responsible for the dark lines. As the radiation from a source of continuous light passes through a gas made of a particular chemical element, the electrons will absorb the photons, the electrons raising their own energies in the process. Because a given element has a particular electronic structure, absorptions relating to it will occur only at particular wavelengths associated with that element (or ion). Hydrogen produces only a few absorptions (in the red at 6563 Å, the blue at 4861 Å, respectively called Hα and Hβ, as well as a few others); helium, with two electrons, has many more, and iron has hundreds of thousands. But whatever the number, for a given atom or ion (or molecule, a combination of atoms that makes chemical compounds), they are always in the same place in

the spectrum. We can therefore sense the presence of hydrogen or any element to the distant reaches of the Universe. In the Sun's photosphere, the deeper, denser, hotter gases produce a continuous spectrum that must pass through higher, cooler, less-dense gases that superimpose their absorptions. By comparing all the line positions with laboratory measurements, we find out what is in the Sun. Of the 90 or so natural elements that exist in the Earth's crust, we have found 68.

Some of the solar absorption lines are very strong, extracting great amounts of energy from sunlight; examples are singly-ionized calcium, Ca^+ (calcium atoms with one electron stripped away), neutral sodium, and hydrogen. Other rarer elements like cesium and tin have only very weak lines that extract little energy and are hardly noticeable against the colored background. The 20 or so elements seemingly missing from the solar gases must simply have lines that are too weak to see.

The strengths of an element's absorption lines depend only to some extent on the element's abundance. Of much more importance is the efficiency of absorption, which, for example, is much greater for ionized calcium than it is for hydrogen. The origins of the efficiencies lie in the atoms' electronic structures. Though the electrons are sometimes said to orbit the nucleus, they behave nothing like a planetary system. In the simplest sense, electrons can exist only in orbits that have specific energies and orbital radii that lie above minimum, or "ground," values. Think of the atom as a ladder. You can stand on the floor, or on any of the rungs (which are real, even though empty), but nowhere in between. It requires energy to climb the ladder. The farther you ascend, the more energy you expend and the more you can release when you jump down.

Electrons can climb the ladder when atoms collide or when they absorb photons from the flow of energy. The energy-rungs are responsible for the discrete nature of the absorption spectrum. The absorption of a photon of a specific energy – that of the energy difference between any two rungs – can make an electron go from one rung to another; when absorbed, that photon is removed from the flow of energy, and if enough are picked off by enough atoms, an absorption line is born. Rungs do not have to be next to each other for a jump to occur; the electrons can skip intermediate ones. As a result, a huge array of lines is possible. If the electrons jump *downward*, we see the opposite phenomenon: *emission* lines, *bright* lines of color at specific energies or wavelengths. Each kind of atom or ion has a different kind of ladder with a different number of rungs in different places. As a result, each kind of atom or ion has a different spectrum.

The optically-visible hydrogen lines can be produced in the solar photosphere only by electrons that are already on the second rung of the hydrogen ladder. Most people in the world stand on the floor; at any time only a few stand on the rungs of ladders. The same is true of atoms. There are so few electrons on the second rungs at any one time that the hydrogen absorption lines are weak even though there is a huge number of ladders. The ionized calcium lines, however, come from the floor, where the calcium ions have almost all their line-producing electrons. As a result, they can *all* absorb from the continuum. The efficiencies of absorption involve how
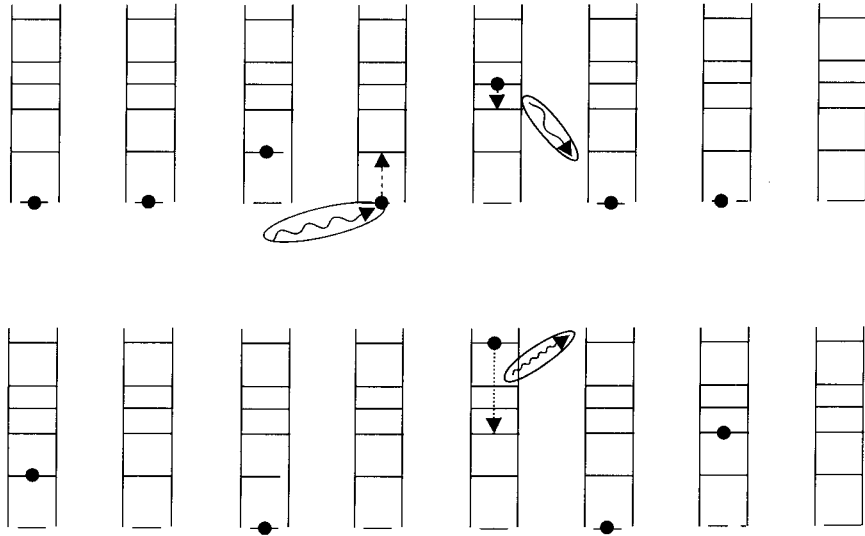
Figure 1.5. A collection of atoms is depicted as a set of ladders, the rungs of which increase upward in energy. Most electrons are on the floor, but a few (the number hugely exaggerated here) have been kicked up to various rungs by collisions. Electrons can jump downward with the emission of photons (wavy arrows) with energy differences equal to the energy differences between rungs; or they can absorb photons with the same specific energies. Photons trying to get through a complex set of atoms in the outer solar layers are absorbed at specific wavelengths to produce the solar spectrum.

many electrons at any given time are on whatever appropriate rungs multiplied by the probability that such an electron will actually absorb light.

When, after about 1920, astronomers were able to take these efficiencies into account, they found that the Sun consists primarily of hydrogen. Analysis of other data, including direct measurement of the matter that flows from the Sun past the Earth (the "solar wind"), has shown the Sun to be about 91% hydrogen and 9% helium. These numbers add to 100%; the rest of the elements are in the decimal places. Less than two-tenths of one percent is filled with all the other elements of nature. Oxygen leads, then carbon, neon, nitrogen, and the rest. There is no reason to think that most stars should be differently composed, and in fact for the most part they are not (though there are some wonderful exceptions).

From the depths

The ever-present solar spectrum suggests a quiet peace, and the stars of the night-time sky almost define serenity. But the Sun, and by implication the stars, are anything but quiet, as shown by the changing granulation pattern and the ephemeral sunspots, which are wards of the solar depths, the convection of the outer third of the Sun creating them both.

Sunspots were watched for over two centuries before astronomers saw that they were cyclic: the number of spots on the Sun at any one time varies with an irregular

period that averages 11 years. At the peak of the cycle we see hundreds of spots, at minimum they can disappear altogether. The spectrum helps us here too. If a gas absorbs radiation while it is in a magnetic field, the absorption lines will be split into twos, threes, or more (the "Zeeman effect"), the difference in wavelength between the components telling the strength of the magnetism. Sunspot spectra are split, magnificently so. The Sun has a global magnetic field somewhat like that of the Earth. But within the spots, the field strength increases to thousands of times terrestrial. Sunspots tend strongly to come in pairs that have different magnetic directions. In one hemisphere (as defined by the rotational equator and poles), all the pairs will be aligned in the same direction; in the other hemisphere, they are aligned oppositely. After the completion of the 11-year cycle, the spots switch directions, returning to their original orientations after 22 years have passed.

The electrons in a wire that is moving in a magnetic field flow with an electric current and a flow of electricity will produce a magnetic field. The solar magnetic field is similarly generated by movement of its ionized gases, by a combination of rotation and the deep convection. In turn, the "differential" rotation of the Sun (that it rotates faster at the equator than at the poles) seems to wrap up and concentrate solar magnetism. Convection locally lifts the field upward, forcing it to pop through the surface in great loops; the spots are formed at the points where the loops exit and enter the photosphere. The intense, concentrated magnetism inhibits the convection, chilling the surrounding area; as a result, the gases radiate less and appear dark against the photospheric background. The loops are highly unstable, causing the spots to change their structures; they can short-circuit each other and collapse, and thereby release their magnetic energy in vast explosive flares.

The magnetic energy generated deep within the Sun is responsible for creating a huge, enormously hot halo around the photosphere, the solar corona. At a temperature of two million kelvin, the corona's density is so low that it does not follow the Stefan–Boltzmann radiation rule, and is so dim that it cannot be seen against the blue sky. Only when the Moon covers the photosphere in a total solar eclipse does the pearly layer shine through. The corona is confined by the same kinds of loops that create the sunspots. Where the magnetism does not close it up, the thin hot gas easily escapes, in part responsible for producing the "solar wind" in which the Sun loses about 10^{-13} of its mass each year. The solar wind blows past the Earth at a speed measured in hundreds of kilometers per second. Coronal blobs released into the wind by collapsing magnetic fields can disrupt the Earth's field, generate intense electrical activity in the upper atmosphere, and create displays of the northern and southern lights. We are very much in the extended solar environment, our Earth beholden to what happens far below the surface.

Yet the true essence of the Sun lies even deeper, far below the convection layer. Limb darkening shows us that the temperature of the Sun (and by analogy that of any star) climbs as we proceed inward. Theory shows the same thing. Limb darkening gives us information on only the outer solar skin, while theory takes us deep inside, right to the center where we find the source of solar energy and support.
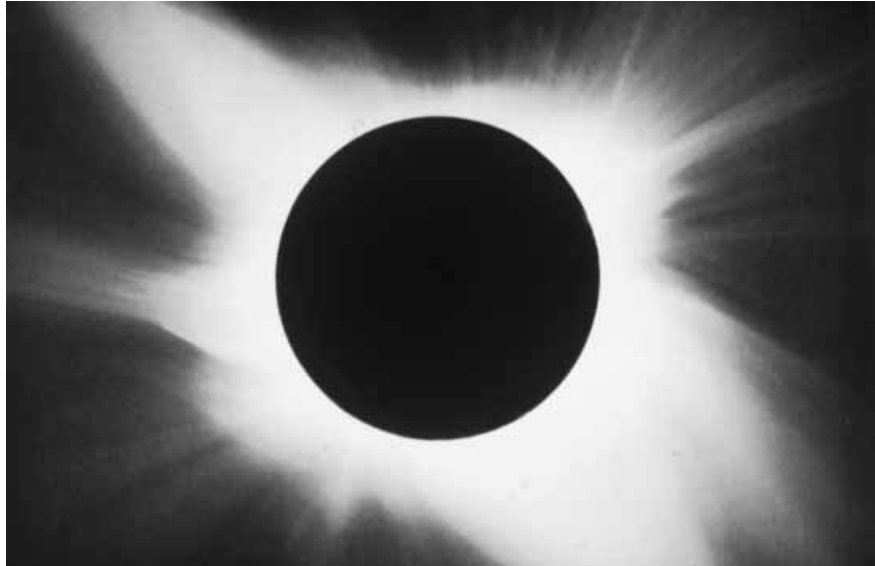
Figure 1.6. Magnetic loops that emerge from the Sun are made visible by confining (and heating) the thin, hot (two million kelvin) gas of the Sun's corona, from which blows the solar wind. [AURA/NOAO/NSF.]

A star is a battleground for the four "forces of Nature," those that act over a distance. The result of the contest is energy in the form of heat and light accompanied by the usually slow, but sometimes violent, aging of the star. The best known of the forces is gravity. Gravity, first described by Isaac Newton, draws all matter to all other matter, all atoms to all other atoms. It is also weakest of the four forces. We know it so well because it cannot be neutralized and because it acts over all space, its strength away from any mass decreasing according to the inverse square of the distance. It is the driving and organizing force of the Universe, acting to assemble matter, and is responsible for the creation of stars and their embracing galaxies.

The next one up in strength is the "weak force," which, unlike gravity, acts over only the size of the nucleus of the atom. It is responsible for various kinds of radioactive decay, in which one kind of particle, or one kind of atom, changes into another with the release of energy. Third is the electromagnetic force, which can manifest itself through electromagnetic radiation – light. Like gravity, it acts over all space but, unlike gravity, has two associated directions. The electric charge can be either positive or negative (the charges carried respectively by protons and electrons), and therefore electricity can neutralize itself. The normal atom contains equal positive and negative charges, and from a distance is neutral and safe. Only when the charges are unbalanced do we feel the power of the electromagnetic force directly (on an atom-to-atom basis 10^{35} times stronger than gravity), as anyone who has stuck a finger into a light socket will readily attest.

The greatest force of all is, by contrast to the weak force, the "strong force,"

which again acts over only the dimension of the nucleus. It is attractive in nature, and holds the particles of the nucleus together (and is thereby also called the "nuclear force"). Carried by both protons and neutrons, it is so strong that it can keep the nuclear protons (whose similar charges try to repel one another) clasped within its grip.

The balance of these forces makes the Sun work and give light to the day. A star contains enormous gravitational energy, its self-generated gravity trying perpetually to squeeze the gas together to make the star as small as possible. Gravity performs like the driving piston in an engine: as the gas is squeezed to higher density, it also heats. As we plunge into the heart of a star, any internal layer must carry an ever-greater load than the one above it, so it must be under higher pressure and hotter as well. Temperature therefore climbs as we proceed inward, the atoms moving ever-faster and becoming increasingly ionized as a result of violent atomic collisions. About three-fourths of the way into the Sun the temperature hits 10 million K. The speeds now become so great that even the repulsive force produced by their similar charges cannot keep them very far apart. A few can be driven so close that the strong force makes the protons stick.

Yet even the strong force lacks the strength to make two electrically-repelling protons join. During the brief moment the protons linger in company, one of them can release its positive charge via the weak force and become a neutron. The repulsive force suddenly disappears, and the two – the proton and new-born neutron – are bound by the strong force. The result is an "isotope" of hydrogen. The nucleus is still hydrogen because of the one positively-charged proton, but is a heavy version with an attached neutron. Since there are two particles now in the nucleus it is called hydrogen-2 (or ^{2}H, where the number of particles in the nucleus is given by the superscript), and more commonly "deuterium."

The positive charge flies away from the nucleus as a positive electron, as anti-matter, normal matter with reversed charges. The Universe is mostly normal stuff. It has to be, as matter and antimatter cannot co-exist; they annihilate each other on contact with the release of energy. The positive electron – a "positron" – cannot get very far within the dense gas before it hits a normal negative electron and the two disappear. In their place appear two high-energy gamma rays. The Sun, through the compressive force of gravity and the actions of the strong and weak forces, has created energy from matter via Einstein's most famous equation E (energy) $= m$ (mass) $\times c^2$ (speed of light)^2, the energy flying off, thanks to the electromagnetic force. Accompanying the positron is a near-massless (perhaps really massless) neutral particle, a "neutrino," that carries additional energy.

Almost as soon as the deuterium is made, another high-speed proton invades the nucleus and is captured by the strong force, which with three particles is now able to tie two protons together, creating an isotope of helium, ^{3}He, as well as another gamma ray. Finally, two of these collide, resulting in ^{4}He and the release of a pair of protons. In this "proton–proton" chain, four protons have melded into one atom of helium.

Gamma rays are deadly, and life on Earth would be impossible if we were in their full glare. We are rescued by the Sun's vast outer envelope, the same one that raises the temperature of the core to the heights that make the fusion reactions possible in the first place. The gamma rays cannot penetrate the envelope directly. Instead, they are immediately absorbed by atoms and then re-emitted. Gradually the energy works its way through the outer layers. Since these are cooler than the inner layers, the emitted photons must on the average have lower energies. But since once energy is created it cannot be destroyed, there must be more photons to make up the difference. As a result, a single gamma ray created in the solar core will – after nearly a million years – result in the release of thousands of optical photons – those seen with the eye – from the solar surface. The neutrinos, on the other hand, speed silently and immediately from the solar center right to the Earth, where with great difficulty we can detect them for a direct "look" into the solar center and a confirmation that the reactions indeed take place as predicted.
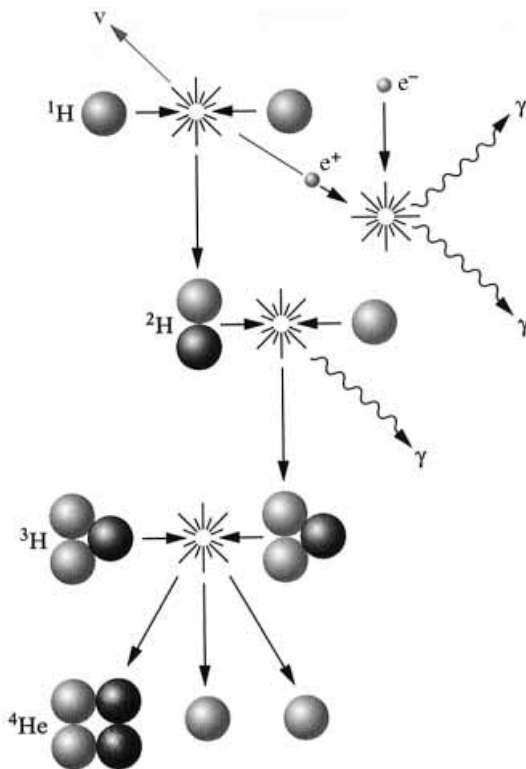
Figure 1.7. The center of the Sun is so dense and hot that four protons or atoms of hydrogen (the lightly shaded spheres) can fuse to become one atom of helium via the proton–proton chain. The chain first makes deuterium when a captured proton turns into a neutron (dark sphere) with the release of a positron (a positive electron), labelled e$^+$. The deuterium absorbs another proton to become light helium, ^{3}He, which undergoes another reaction to make normal helium, ^{4}He. Energy is released as neutrinos (ν), near-massless particles that fly unimpeded from the Sun, and as gamma rays (γ) created by the collisions of positrons and electrons. [From *Cosmic Clouds* by J. B. Kaler © 1997 by Scientific American Library. Used with permission of W. H. Freeman and Company.]

Other stars

The Sun is but one of 200 billion stars in our local collection, our Galaxy, if "local" is a term that can be used for a structure that is some 10^{18} km across. Such distances require the use of a larger unit. The light-year (l.y.), the distance a ray of light – a photon – travels in a year at a speed of 300,000 km/s, is 9.5×10^{12} km long. The distance to the Sun, the "Astronomical Unit" (AU), is 150 million km (8 light-minutes), so the light-year has a length of 63,000 AU.

Decades of research have shown that our Galaxy is dominated by a thin disk 80,000 or so light-years across that contains over 90% of the stars. We are located
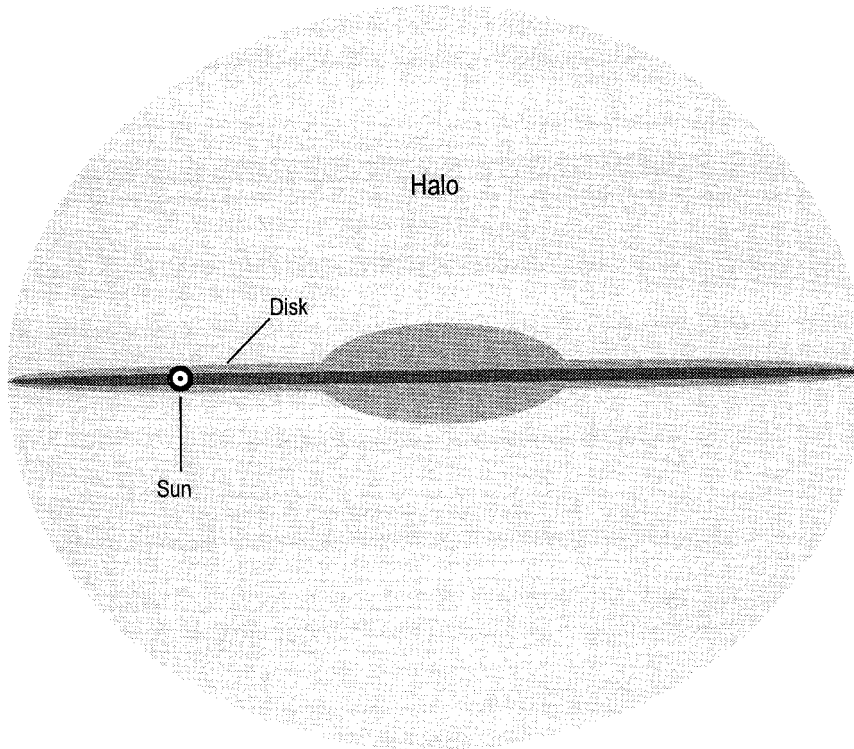
Figure 1.8. Seen edge-on, our Galaxy consists of a thin disk that contains most of the stars surrounded by a sparsely populated halo. The Sun is out toward the edge (about 25,000 light-years from the center). The disk encircles us as the Milky Way. The disk and halo faintly extend much farther than indicated here.

about 25,000 light-years from the center, rather well off toward the ill-defined edge. The disk rotates – the Sun taking about 250 million years to go about the center – and is structured into a set of flowing spiral arms. Surrounding the disk is a somewhat spherical, sparsely populated halo that the disk slices in half.

Ours is hardly the only galaxy, a suspicion confirmed by Edwin Hubble in the 1920s when he found that fuzzy blobs observed for centuries were distant vast collections of stars. They in fact swarm the Universe, tending strongly to clump into huge clusters. There are numerous kinds, but three broad varieties dominate. The loveliest are the spiral galaxies like our own. Since we cannot see ours from outside, other spirals tell us a great deal about the system in which we live. The elliptical galaxies on the other hand are seemingly simple ellipsoids that exhibit neither disks nor spiral arms. Another smaller fraction consists of irregular galaxies with little structure. Tucked in among them all are vast numbers of small assemblies that look like shredded debris. Given enough time the Hubble Space Telescope could probably detect a trillion (a thousand billion or a million million) galaxies, many much larger than our own.

Figure 1.9. Other spiral galaxies tell us how ours is constructed. On the left, NGC 891, presented edge-on, shows the thinness of its disk and its thick lane of interstellar dust. Seen more face on, the disk of M74 displays a complex set of spiral arms somewhat similar to ours. [*Left*: Mt Wilson Observatory. *Right*: AURA/ NOAO/NSF.]

Because the Sun lies within our Galaxy's disk, we see the disk and its billions of stars surrounding us in a great thick white band called the Milky Way. The subject of myriad mythologies, the Milky Way was revealed as made of stars by Galileo when he turned the first astronomical telescope on it in 1609. At its best, it is a spectacular sight that unfortunately is easily lost in the glare of artificial lighting. Its enormously complex structure is created by thick clouds of dark dust that lie in the spaces between the stars and that appear to divide the Milky Way into parallel tracks. This dust lane is easily seen in images of other galaxies set edge-on. The dust, allied with massive clouds of gas, blocks the light of stars. Within the clouds, the temperature plummets to near absolute zero, allowing the contraction of the gas into new stars. Stand out under the thickest parts of the Milky Way and look into its black hearts: stars are being created at that moment in the hidden darkness. Our own Sun came from such a cloud 4.6 billion years ago.

Aside from its observational accessibility (and its third, life-holding, planet), our Sun has no special characteristics that set it apart from the other stars of the Galaxy, and lies very much in the middle of the ranges of all stellar properties. Measurement of such properties for other stars has in one way or another occupied astronomers for 2000 years. The simplest of them is apparent brightness. About 150 B.C., the great Greek astronomer Hipparchus divided the stars into six brightness categories we now call magnitudes, the brightest (the top 21 stars) called first magnitude, the faintest the eye can discern, sixth magnitude. Nineteenth-century astronomers recognized magnitudes as a logarithmic brightness scale, and established a quantitative system in which first magnitude was exactly 100 times more luminous than sixth. If a difference of five magnitudes corresponds to a factor of 100 then one magnitude refers to the fifth root of 100, or 2.512 . . . (multiply it by itself 4 times). To calibrate the scale, the average of a collection of faint stars was arbitrarily set at 6.0 and the rest scaled to them.

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Hipparchus's original first-magnitude stars contain a very wide range of brightness. Seven of the most brilliant (including Alpha Centauri, Vega, and Arcturus) had to be moved to magnitude zero, and two to −1. The scale is open-ended, allowing us to extend it to bright planets and to telescopically observed stars. With binoculars we can see to eighth, with a typical backyard telescope to perhaps 12th or 14th, and with the Hubble Space Telescope to 30th. Do not let the small numbers fool you; each set of five magnitudes is another factor of 100, so that 30th magnitude is a trillion (10^{12}) times fainter than Vega, itself shining at magnitude 0.03. Vega in fact now represents the modern standard, to which all stars are ultimately referred.

The apparent magnitude – the brightness the star appears to be in the sky – depends upon the intrinsic luminosity of the star and on its distance. The derivation of stellar distances begins with measurements of the parallaxes of the nearby stars, the minute shifts in position caused by the Earth moving in orbit about the Sun. If you look at any object from two points of view, it changes position relative to the background. Know the distance between the points and the angle of shift and you can calculate the distance. In the cases of stars, the angular shifts are so small that they were not measured until 1846; the largest such shift, for Alpha Centauri, is only 1.48 seconds of arc. (There are 3600 seconds of arc in a degree; for comparison, the full Moon is one-half degree across.) As a result, Alpha Centauri (actually a dim companion to it) is the closest star to Earth. The "parsec," the distance unit used in professional astronomy, is defined as the inverse of the parallax (formally, one-half the full shift) expressed in seconds of arc. The distance of Alpha Centauri is therefore $1/0.74 = 1.35$ pc. There are 3.26 light-years in the parsec, so Alpha Centauri is 4.4 light-years, or 280,000 AU, away; we see the star as it was over four years ago.

Though parallaxes were long restricted to the immediate vicinity of the Sun, modern technology, including the hugely successful Hipparcos space-craft, extends the technique to over 1000 light-years, which defines a volume that encloses millions of stars of different kinds. We can then use these parallaxes to calibrate other distance methods, allowing us to work our way outward to distant limits of the observable Universe, in which distances are measured in billions of light-years.

Figure 1.10. The band of the Milky Way is the disk of our Galaxy seen from a vantage point out near its edge. [Akira Fujii.]

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Figure 1.11. The southern hemisphere's Alpha Centauri (the left-most bright star), 11 degrees to the east of the Southern Cross (at right), lies only 4 light-years away. [Akira Fujii.]

Even the naked-eye stars cover an enormous range in distance, to far beyond a thousand light-years. Alpha Centauri, to us the third brightest star, is (as revealed by the telescope) actually a double star, two close stars in mutual 80-year orbit about each other on average separated by about the distance between the Sun and Saturn. The brighter of the pair is remarkably like our own Sun; by itself it would still be the third brightest star in the sky, but it is apparently bright (that is, bright to the eye) only because it is so close to us. The southern star Canopus is brighter in appearance despite being over 200 light-years away; obviously, Canopus is much the more luminous star. To know true stellar luminosities, we must have some way of removing the distance, and use a system of *absolute* magnitudes, M, which are the apparent magnitudes, m, that the stars would have were they at a standard distance of 10 parsec or 32.6 light-years. Since the apparent brightness of a pinpoint of light depends on the inverse of the square of its distance, we can easily calculate absolute magnitudes from apparent magnitudes once the distances are known.

Of course there are some complications in the magnitude scheme. The magnitude of a star also depends on its temperature and therefore also on its color. For example a star could be very luminous but so cool that it radiates mostly in the infrared, very little energy sneaking into the visible. The star would therefore appear quite red to the eye and (compared to other stars) relatively dim. Similarly, very hot, blue stars radiate a great deal of their light in the invisible ultraviolet. The apparent brightness of the star therefore depends on the color of the light in which we make the magnitude observations, which must be specified for the measurement to make any sense. Traditionally we use yellow light, which is appropriate to that seen by the

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human eye; such magnitudes are therefore referred to as "visual magnitudes," or V. The "absolute visual magnitudes," called M_V, are the astronomers' basic measure of visual luminosity. Total luminosity can be found and related to absolute visual magnitude through the star's temperature.

Spectra: at the heart of it all

Star colors and temperatures are related to the stars' spectra. When astronomers first began observing stellar spectra (with simple prisms placed at the foci of their telescopes) in the early nineteenth century, they were confronted with a highly confusing situation: stars exhibit a wide variety of different kinds, of which the solar spectrum is but one example. Some, like that of Vega, were seen to be supremely simple, dominated by a progression of hydrogen lines. Others, like those of Capella, Aldebaran, and the Sun, were filled with metal lines, and still other spectra had the complex bands of molecules.

The initial step needed to understand the natures of the stars was the classification of these varied spectra. The first enduring scheme was developed in Rome by Father Angelo Secchi, who divided the stars into five types that are roughly comparable with the colors that can be distinguished with the human eye. Before the turn of the century, the observations, by then being obtained photographically, were good enough that a more refined system was needed. Developed at Harvard College Observatory in the United States by Edward C. Pickering, Williamina Fleming, Antonia Maury, and Annie Cannon, the scheme used Roman letters that originally ordered stars according to the strengths of the hydrogen lines, but which were actually based upon a variety of criteria. After several letters were dropped or merged into others, and the system reorganized according to the continuity of the appearance of all the absorptions, the spectral sequence familiar to all astronomy students – OBAFGKM – emerged. Recent discoveries have extended it to yet cooler stars and substars (those not massive enough to make the grade), these now included in new class "L."

While the A stars feature strong hydrogen lines, those in class B (where hydrogen is still strong) are possessed of neutral helium; in class O the ionized helium lines are strong. As we descend below class A, the stars develop strong ionized metal lines, then neutral metal lines, and in class M molecular bands dominate. It was obvious even to Pickering and Cannon that the system correlated with the colors of the stars and therefore with their temperatures, which we know run from about 50,000 K at the hot (O) end down to about 2000 K at the cool end of class M. The 6000 K Sun, rather in between, with strong ionized and neutral metal lines, is a G star. As spectroscopy improved, Cannon decimalized the letters to discriminate better between stars. The Sun is a G2 star, cooler than one at G0 but hotter than G5.

By 1930 the principles behind the sequence were understood. All the different kinds of spectra are produced by stars with about the same compositions, about 90% hydrogen, 10% helium, and commonly somewhat less than 0.2% everything else.
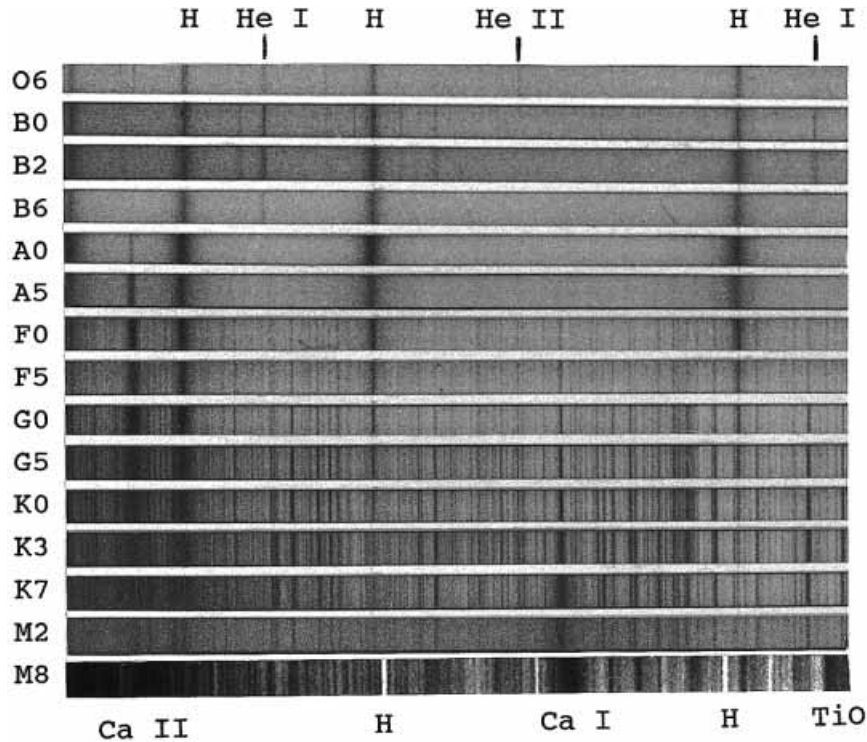
Figure 1.12. The standard stellar spectral sequence (*sans* L), seen here in the violet (between about 3900 Å and 4450 Å), descends from hot O6 (41,000 K) to cool M8 (2200 K). Hot stars have strong hydrogen lines that peak in class A then diminish downward, disappearing in class M. The hotter O and B stars display lines of helium, while the cooler F, G, and K stars show numerous lines of metals. The strengths of the singly-ionized calcium lines (one of which is blended with the left-hand hydrogen line) first increase with descending temperature, then decrease as the strength of the neutral calcium line increases. The bottom M8 spectrum displays a black band of the titanium oxide molecule. [*Atlas de Spectres Stellaires*, N. Ginestet, J. M. Carquillat, M. Jaschek, C. Jaschek, A. Pédoussaut, and J. Rochette, Observatoire Midi-Pyrénées and Observatoire de Strasbourg, 1992; bottom spectrum from *An Atlas of Representative Stellar Spectra*, Y. Yamashita, K. Nairai, and Y. Norimoto, University of Tokyo Press, 1978.]

(There are some fascinating variations on this theme that will be important later.) The differences do not just correlate with temperature but are *produced* by temperature, which changes both the efficiencies of line absorption and the ionization level of the stellar photospheric gases.

Look, for example, at hydrogen, whose lines are created in the outer layers of the star by absorption of photons by electrons on the second rung of the hydrogen energy ladder. As temperature rises, the gas has more internal energy as a result of the atoms' faster movements. There are therefore more electrons bounced upward to the higher rungs as a result of more vigorous atomic collisions. The hotter A stars have more electrons on the second rung of the hydrogen ladder than do solar-type G stars, and their hydrogen lines are stronger. Toward the bottom of the spectral

The spectral classes

Type	Color	Temperature (K)	Description
O	bluish	28,000–50,000	ionized helium, hydrogen
B	bluish–white	10,000–28,000	hydrogen, neutral helium
A	white	7500–10,000	strongest hydrogen
F	white	6000–7500	hydrogen, ionized metals
G	yellow–white	4900–6000	ionized metals, hydrogen
K	yellow–orange	3500–4900	neutral metals
M	orange–red	2000–3500	neutral metals, molecular oxides
L	red	<2000	neutral metals, molecular hydrides

sequence, among the M stars, there are so few electrons on the second rung that the hydrogen lines disappear, even though the stars are still 90% hydrogen. Above about 10,000 K, the collisions are so vigorous that hydrogen's electrons can be ripped away to create hydrogen ions. The hydrogen lines (created only by the neutral atoms) therefore diminish in strength, though still remaining prominent right through the O stars.

Neutral helium's absorption lines arise from the second rung in its energy ladder as well. However, helium's second rung is twice as high as hydrogen's, and it takes much more energy – and higher temperatures – to kick an electron into it. As a result, we do not see helium absorptions in the Sun's photospheric spectrum; they in fact do not become visible until we reach the temperatures of the B stars. At yet higher temperatures, helium ionizes, its lines becoming prominent only in class O.

At high temperatures, metals are highly ionized, with two or more electrons missing. As we drop in temperature from the A stars, metals with only one electron missing become prominent, singly ionized calcium dominating the solar spectrum. Below class G, into K and M, the gas is no longer warm enough for the collisions to support even singly-ionized calcium, and its lines decrease in darkness, to be replaced by those of the neutral state (neutral calcium for example). Eventually, the temperature is low enough to allow molecules – combinations of atoms that are easily broken apart by collisions with atoms – to form. Even in the Sun we find a bit of CH and a few other hardy molecules, especially in the cooler sunspots. Among the cooler M stars (and in class L), molecules dominate, the cooler M stars recognizable by powerful bands of titanium oxide, TiO (which happens to have its absorptions in the optical part of the spectrum).

Variety

The luminosities and temperatures of stars are traditionally presented on a graph in which absolute visual magnitude is arrayed against spectral class. The principal feature of this "Hertzsprung–Russell diagram" (or HR diagram, named after Ejnar
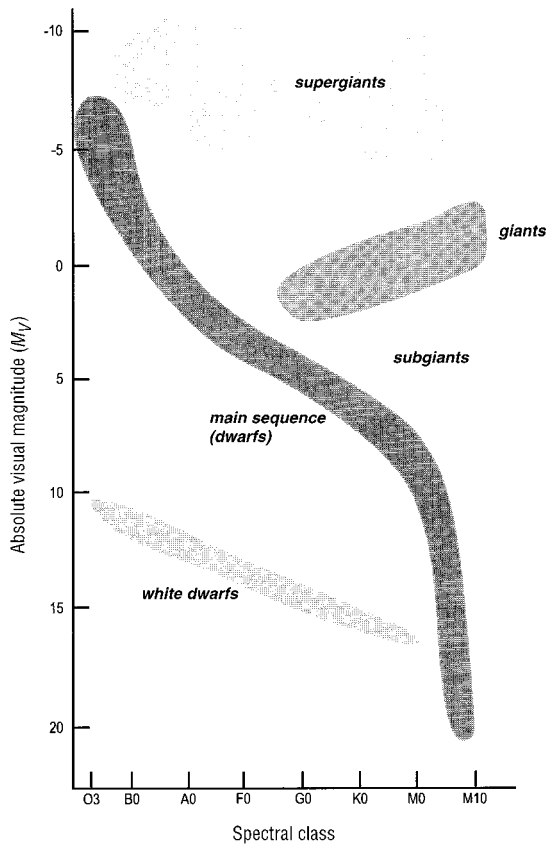
Figure 1.13. The HR diagram shows the luminosities of stars (expressed by absolute visual magnitudes) plotted against temperatures (expressed by spectral classes, excluding class L). The main (or dwarf) sequence runs from lower right to upper left. It is a mass sequence that starts at eight percent solar on the bottom to about 100 times solar at the top. The other zones represent various stages of stellar evolution in which stars are dying. Stars like the Sun become the giants and then the white dwarfs; higher-mass stars become supergiants and then explode.

Hertzsprung and Henry Norris Russell) is a strip densely packed with stars in which visual luminosity is in some direct proportion to temperature. That is, as the stars' surface temperatures increase, so do their absolute brightnesses. In observational terms, as we proceed through the spectral sequence, from M through G to O, absolute visual magnitudes decline from around $+20$ (a million times fainter than the Sun) to about -6 or -7 (over 50,000 times brighter). Such a correlation is in qualitative keeping with the Stefan–Boltzmann law, in which a hot body brightens according to the fourth power of the temperature.

To place these upper and lower luminosity limits in perspective, imagine one of these extreme bodies replacing the Sun. To light the day with a low-end star we would have to be 1000 times closer than we are to the Sun, or a mere 150,000 kilometers (about 100,000 miles), less than half the distance to the Moon. At the high end we would have to be over 200 times farther away than we are now, more than five times more distant than Pluto.

A star's luminosity – its power output – depends on two quantities. Temperature determines only the amount of energy radiated per unit area (square meter or square centimeter of surface). The more square meters of surface possessed by the star, the brighter it will be, so luminosity also depends on radius or diameter. The surface area of a sphere depends on radius squared. As a result, luminosity varies as T^4 times R^2. If we know the luminosity and temperature, we can find the radius. Luminosity is related to absolute visual magnitude; we must only be sure to factor in the invisible ultraviolet and infrared radiation respectively produced by hot and cool stars (which can be quite large). The stars in this "main sequence" brighten even faster with increasing temperature than mandated by the Stefan–Boltzmann law, showing that the stars are also increasing their surface areas,

or diameters, from about only twice the size of Earth at the low end to over 10 solar diameters at the high end.

Hertzsprung's and Russell's greatest discovery, made in the early twentieth century, was that many stars do *not* lie on the main sequence. The principal additional feature of the diagram is a central band that goes up and to the right, in which luminosity increases as temperature *decreases*. To be both bright and cool requires great size. These stars were therefore rather naturally called "giants," discriminated by calling those of the main sequence "dwarfs." (In spite of the size of bright main sequence stars, the terms "main sequence" and "dwarf" are synonymous.) Giants can easily encompass the inner Solar System. We also see cool stars up at the top of the HR diagram that are even brighter than giants; these "supergiants" can encompass much of the *outer* Solar System. We also find stars *below* the main sequence, stars that are both hot and quite faint. These must be terribly small, even smaller than Earth itself. The first ones found were white, so the name "white dwarf" was applied, a term still used even though some are red and others blue.

These various stellar zones on the HR diagram were formalized in the 1940s by astronomers W. W. Morgan, P. C. Keenan, and E. Kellman, who placed them into luminosity classes distinguished by Roman numerals: I through V represent supergiants, bright giants, giants, subgiants (stars that fall between the giant and dwarfs), and main sequence dwarfs respectively. The Sun is, finally, a G2 V star.

Much of twentieth-century astronomy has involved the explanation of the HR diagram. The most important quantity is mass. In the long run, nothing much else matters. Masses are derived by the examination of double stars. The story starts almost 400 years ago when Johannes Kepler revealed the laws that govern planetary orbits. In his third law, he showed that the squares of the orbital periods in years were proportional to the cubes of their average distances from the Sun as expressed in astronomical units. (Jupiter is 5.2 AU from the Sun, and orbits in 11.9 years. Squaring the period and cubing the distance yield the same number.)

Newton derived the result theoretically from his laws of motion and the law of gravity and, moreover, found that the orbital period of a planet depends on both the distance of the planet from the Sun and on the sum of the masses of the Sun and the planet. If, for example, you could increase the mass of the Sun, but hold the Earth at 1 AU, the Earth would have to move faster as a result of the increased gravitational attraction, and the period would be less. Consequently, you can determine the sum of the masses of the Earth and Sun from the orbital characteristics of the Earth. Since the Sun is so much more massive than the Earth, the result is effectively the solar mass. Any of the other planets would serve equally well and give the same result.

We can apply the same reasoning to any two bodies in mutual orbit, and therefore to double, or "binary," stars. Ever since William Herschel confirmed the existence of double stars in the late 1700s, astronomers have learned that they are anything but unusual. A prime example is our closest star, Alpha Centauri. Perhaps 80% of the Galaxy's stars are in some kind of double system, the two orbiting each

Figure 1.14. Alpha Centauri is actually a double star, the pair locked together in gravitational embrace and orbiting each other every 80 years. The brighter of the two is remarkably like our own Sun. [AURA/NOAO/NSF.]

other. Multiples are common as well. We see systems in which a star orbits a double at a great distance (double Alpha Centauri has a distant faint companion), pairs of binaries that orbit each other (like Epsilon Lyrae), even (like Castor, Alpha Geminorum) binaries that orbit double-doubles.

Once we have measured the radius of a binary star's mutual orbit we can find the sum of the components' masses. One star does not actually orbit the other, however; instead, each member of a pair of stars swings about a common center of mass that lies between them whose location depends on the *ratio* of their masses. Once we have the sum and ratio, we can calculate the masses of the individual bodies. From hundreds of studies, astronomers found that the main sequence is a *mass sequence*, beginning at the bottom at eight percent the mass of the Sun (the minimum required to run the proton–proton chain), continuing upward through one solar mass in the G stars, to about 20 times that of the Sun among the B stars; theory extends the relation to over 100 solar masses among the O stars. The larger the mass, the more gravitational energy available, the greater the compression, and the higher the temperature at the core. As a result, high-mass main sequence stars are much more luminous than low-mass stars.

The second quantity needed to explain what we see in the HR diagram is stellar age. By analogy with the Sun, the entire main sequence is a stable zone of hydrogen fusion, nuclear "burning" (a common synonym for "fusion") supporting the star against the pressure supplied by gravity. Stars are remarkable self-regulating devices. As the fuel in the interior is consumed the core shrinks a little in response,

which drives the temperature up somewhat and causes the remaining fuel to burn (fuse) somewhat faster and the core to eat slowly into the surrounding hydrogen. The result is that the star will reside for most of its life on the main sequence, only very slowly brightening and/or cooling at its surface as the fuel supply diminishes. The rate of change of position of the stars on the HR diagram is slight and serves only to give breadth to the main sequence and make it into a band. Stars near the left-hand edge are newly formed, while those near the right-hand edge have little time left to them.

When the fuel inside a star is finally used up, and core fusion shuts down, the star begins to die. The lifetime on the main sequence depends on how much fuel is available divided by how fast it is burned. Nuclear burning rates are so sensitive to temperature that high-mass stars live much shorter periods of time than do low-mass stars. The lives of lower-mass stars are so long that no K or M dwarf has ever had time to evolve off the main sequence in the whole 13 (or so) billion-year history of the Galaxy. An O star, on the other hand, can burn out in a few million years, one of the reasons that the high-mass O-type luminaries of a Galaxy are so very rare: they are ephemeral, and in a sense evaporate right before our eyes. Moreover, their births are intrinsically rare as well. For reasons not yet understood, Nature prefers to make long-lived low-mass stars, enough so that half the mass of the Galaxy is tied up in the dim red M dwarfs.

When the fuel is gone, gravity gets the upper hand and the core contracts, releasing gravitational energy, and perversely making the star temporarily brighter and the envelope larger. Stars like the Sun expand to become giants, those in the upper mass ranges becoming supergiants. The giants lose their extended envelopes and the cores become exposed as tiny white dwarfs. The supergiants explode in extraordinary blasts, "supernovae," that expel vast quantities of their matter into space leaving behind amazingly small bodies: neutron stars that are no larger than a small town, or even the fabled "black holes" that are so dense that nothing, not even light, can escape from them.

The final result is that even though two quantities – mass and age – are needed to describe the HR diagram, the second, age, also depends on mass, making mass supreme in the life of a star. The whole story of stellar evolution is one of a perpetual attempt of a star to contract, first starting with its condensation out of dusty interstellar gases. The main sequence is the first of many pauses and transitions along the way that give life and sparkle to the HR diagram. The stories of the main sequence and the other stages that follow will be told in the ensuing chapters by looking at extreme limits in a variety of categories, of stars at the edge, at the faintest, coolest, hottest, brightest, biggest, and smallest, as we see one extreme marvelously transform itself into another. With this setting in hand, we will then look at the outer limits of age, at the youngest and oldest stars, and finally at some of the stranger stars not already encountered.